PERFORMANCE CHARACTERIZATION OF THE ASTRIUM 10K DEVELOPMENTAL CRYOCOOLER

C. H. Y Bruninghaus[1], J. P. Kallman[1], B. J. Tomlinson, Jr.[1], E. Myrick[2]

Air Force Research Laboratory, Space Vehicles Directorate
Kirtland AFB, NM 87117-5776, USA

Ballistic Missile Defense Organization
Arlington, VA 22202, USA

ABSTRACT

To satisfy future Air Force mission requirements, the Air Force Research Laboratory (AFRL), sponsored by the Ballistic Missile Defense Organization (BMDO), led a development program for a proof-of-concept cryocooler designed to support a cooling load of 45mW at 10.4K. Under the technology development program, Astrium (formerly Matra Marconi Space) in Stevenage, United Kingdom, developed a Stirling cycle cryocooler with four Oxford flexure compressors and a two-stage expansion cold end. The cooler was delivered to AFRL, instrumented, and integrated with a 36-inch vacuum chamber for performance characterization and long life endurance evaluation. This paper contains a short description of the cooler's physical components. Also presented are cool down curves, characteristic load lines, and lessons learned during the characterization process. The cooler will enter a long term endurance evaluation after completion of its performance characterization.

INTRODUCTION

The Astrium 10K development model cryocooler is a two-stage Stirling cycle device, which was designed to lift 45 mW of heat at 10.4K. The design heritage of this cooler comes from the Rutherford Appleton Laboratory (RAL) "Oxford" design. The program utilized existing compressor technology, which required four compressors to produce the gas compression necessary to reach 10K. Astrium also modified their existing 20K cold head design, using geometry and regenerator material recommendations from RAL. This gave the cooler significant design and reliability heritage. This unit's lifetime is expected to exceed 50,000 hours.

AFRL is characterizing the Astrium 10K cryocooler to examine its nominal performance in space-like conditions, match the performance witnessed at the contractor's

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14. ABSTRACT
To satisfy future Air Force mission requirements, the Air Force Research Laboratory(AFRL), sponsored by the Ballistic Missile Defense Organization (BMDO), led a development program for a proof-of-concept cryocooler designed to support a cooling load of 45mW at 10.4K. Under the technology development program, Astrium (formerly Matra Marconi Space) in Stevenage, United Kingdom, developed a Stirling cycle cryocooler with four Oxford flexure compressors and a two-stage expansion cold end. The cooler was delivered to AFRL, instrumented, and integrated with a 36-inch vacuum chamber for performance characterization and long life endurance evaluation. This paper contains a short description of the cooler’s physical components. Also presented are cool down curves, characteristic load lines, and lessons learned during the characterization process. The cooler will enter a long term endurance evaluation after completion of its performance characterization.

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facility, and examine its quasi-steady state and transient performance over a range of operating parameters and environmental conditions.

COOLER DESCRIPTION

The Astrium 10K cooler is comprised of a set of four compressors mounted in two co-axial pairs (to minimize vibration at the base of the support structure), a displacer unit with a momentum balancer, and a transfer line and manifold assembly, which links the compressors and the displacer (Figure 1). The cryocooler system physical characteristics are listed in Table 1. The cooler is driven by Astrium dual drive electronics. Both the cooler and its experimental environment are controlled manually.

The Astrium 10K cooler was integrated with a 36" vacuum chamber at AFRL. The cooler was delivered with a base plate designed for use in a vacuum chamber or on an experiment bench. At Astrium, the cooler was only tested on the bench, where the heat generated by the compressors was rejected by running cooling lines to the compressors as well as through forced convection to the clean room atmosphere. In the vacuum chamber at AFRL, all heat is rejected through conduction to two copper cold plates mounted underneath the base plate, directly under the compressors.

CHARACTERIZATION

The characterization experiments done at AFRL provide an objective evaluation of a cryocooler's mechanical and thermodynamic performance envelope as well as

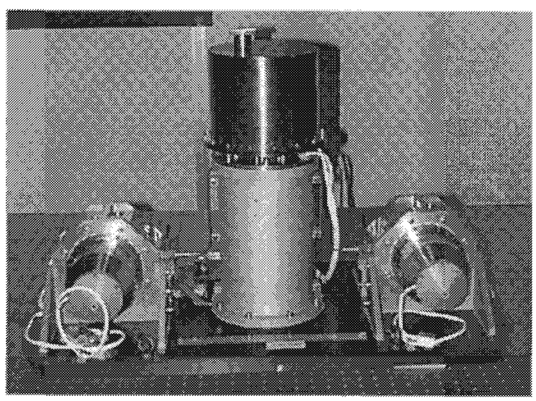

FIGURE 1. Astrium 10K Cryocooler

TABLE 1. Cryocooler System Specifications

Mass of Mechanical Unit	50.5 kg
Cooler Assembly Dimensions (Includes support structure, but excludes base plate and vacuum jacket)	740mm (Length) x 420mm (Width) x 375mm (Height)
Overall Cooler Assembly Dimensions	782mm (Length) x 420 mm (Width) x 477mm (Height)

experimental data for the validation of empirical models developed at AFRL to predict cryocooler performance at conditions for which no experimental data exists.

Upon arrival at AFRL, the cooler was inspected, weighed, and measured to make sure it met contractual requirements. After a short functional test on a bench top, it was integrated with a vacuum chamber, and the characterization experiments began. First, the cooler was allowed to reach thermal equilibrium at its nominal heat rejection temperature. Then it was started, and its cool down curve and the lowest achievable temperature (with no heat load) were recorded.

Table 2 shows the cooler's normal operating conditions. The cooler's nominal stroke length was supposed to be 9mm on all four compressors. However, one of the compressors was damaged during initial testing at Astrium, and as a result cannot be run beyond 8mm without encountering noise problems. Due to this limitation, the normal stroke lengths were established by Astrium as 9.2mm on compressors 1, 2, and 4, and 8mm on compressor 3.

Figure 2 shows a cool down curve for the Astrium 10K. The cooler is normally started up with 6mm stroke length commands. When steady state is reached at 6mm, the commands are increased to 7mm, 8mm, and finally 9.2mm/8mm, while allowing the cooler to reach steady state at each stroke length command level.

TABLE 2. Astrium 10K Cryocooler Normal Operating Conditions

TC1 (K)	TC2 (K)	TC3 (K)	QL (mW)	TR (K)	Ta (K)
Cold End Temperature	Cold End Temperature	Midstage Temperature	Heat Load	Heat Rejection Temperature	Ambient Temperature
10.35	10.51	174.02	45.54	289.91	295.26

Stroke Length 1 (mm)	Stroke Length 2 (mm)	Stroke Length 3 (mm)	Stroke Length 4 (mm)	Stroke Length Displacer (mm)	Stroke Length Balancer (mm)	Operating Frequency (Hz)
9.20	9.21	8.00	9.20	3.00	3.00	30

Icomp1 (Amp)	Icomp2 (Amp)	Icomp3 (Amp)	Icomp4 (Amp)	Phase (Deg)
4.35	4.31	4.10	4.39	55.29

Input Power (W)	Specific Power (W/W)	Wcomp1 (W)	Wcomp2 (W)	Wcomp3 (W)	Wcomp4 (W)	Wdisp (W)	Wbal (W)
145.28	3189.94	42.14	40.09	34.75	43.33	2.00	0.02

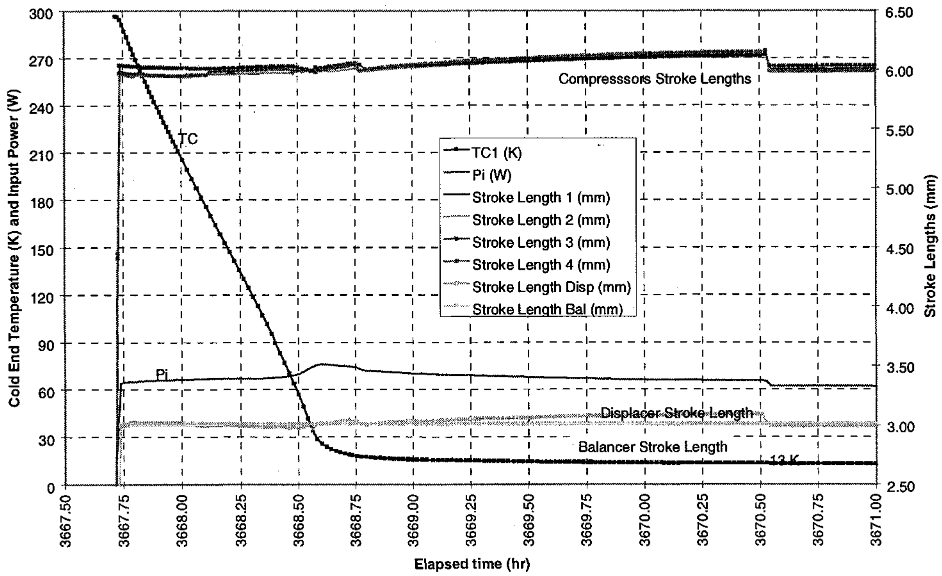

FIGURE 2. 6mm Stroke Length Cool Down Curve

During the characterization process, the cooler's baseline was established. The baseline provides engineers with a diagnostic tool, with which they can track the transient health and performance of the cryocooler. The baseline is a load line done at normal conditions showing cold end temperature vs. heat load. Parameters monitored during the load line include cold end temperature, midstage temperature, cold end heat load, cryocooler case

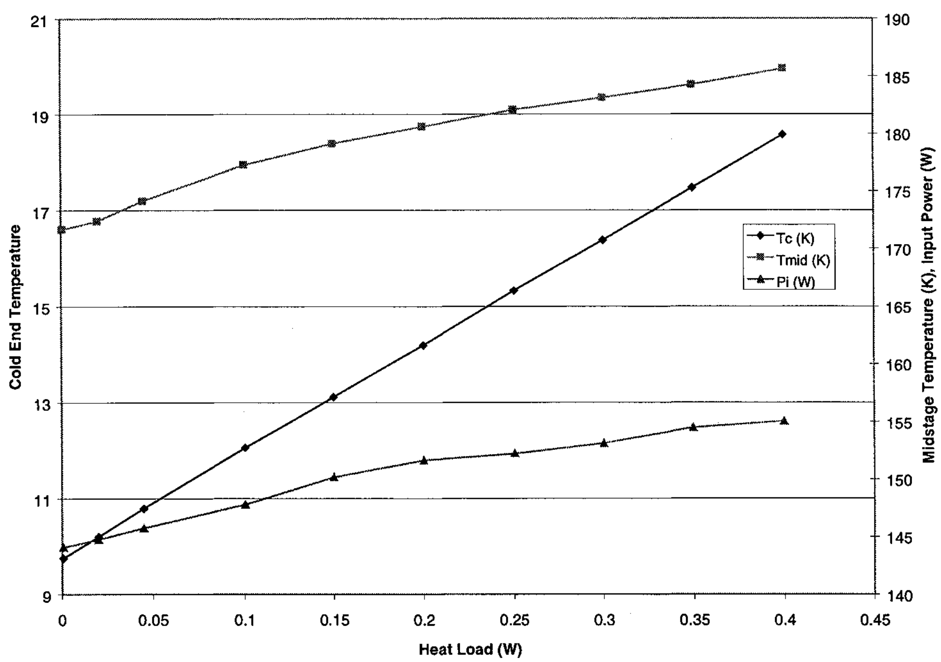

FIGURE 3. Astrium 10K Baseline – Heat Rejection Temperature = 290K

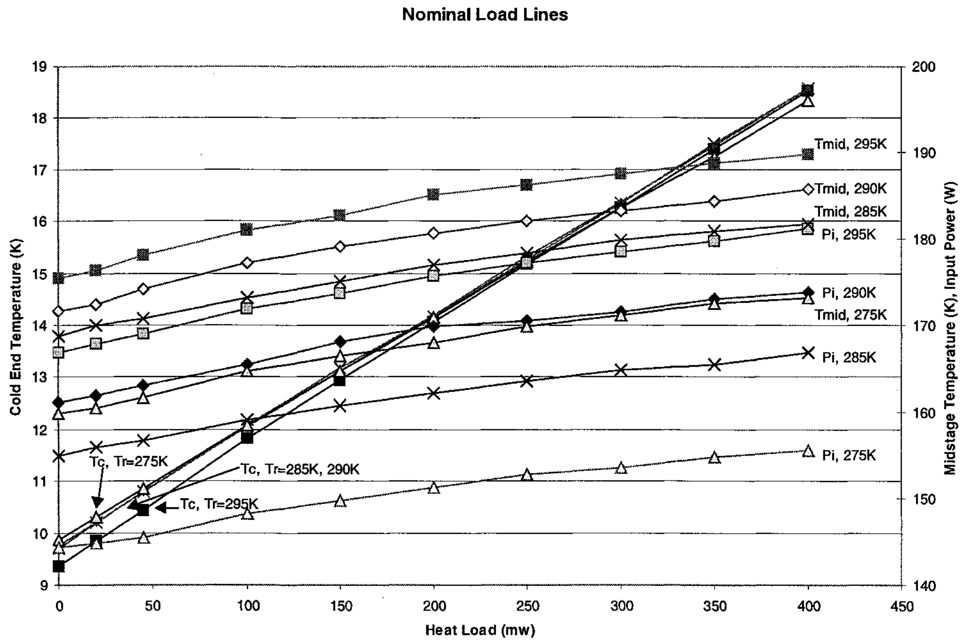

FIGURE 4. Nominal Load Lines (Tc = Cold End Temperature, Tmid = Midstage Temperature, Pi = Input Power, and Tr = Heat Rejection Temperature)

temperatures, compressor and displacer stroke lengths, heat rejection temperature, and input power. The compressor and displacer stroke lengths and heat rejection temperature were controlled and monitored to ensure repeatability of the experiment. The baseline trial is repeated during characterization to ensure that the cooler's performance has not degraded over the course of the experimentation. Figure 3 shows the Astrium 10K baseline load line.

Nominal load lines were done next. These followed the same procedures as the baseline load lines, except that they were done at different heat rejection temperatures. Figure 4 shows the Astrium 10K nominal load lines. The midstage temperature and input power both increase with increasing heat rejection temperature. However, the no-load cold end temperature decreases with increasing heat rejection temperature.

LESSONS LEARNED

One of the first lessons learned was that cryopumping to the cold end occurs at temperatures less than 30K, even in a 10^{-7} torr vacuum. When the cooler was first started up, performance was significantly poorer than what it was at the Astrium facilities. The lowest achievable temperature reached during the first cool down was 10.8K with no heat load. Also, when the cooler was run for long periods of time the temperature would start increasing slowly. Over the course of 5 days, the cold end temperature rose from 10.8K to 17.3K. Cryopumping was suspected as the cause of the temperature rise. The cooler was shut down, and the vacuum level was monitored as the cold end temperature increased. A two orders of magnitude decrease in the vacuum level from 9×10^{-7} torr to 1.2×10^{-5} torr as the cold end reached approximately 36K indicated that contaminants condensed on the cold end were being released (see Figure 5). As a result, the cold end was intentionally cycled between 10K to 40K over the course of three months in an attempt to draw out and remove

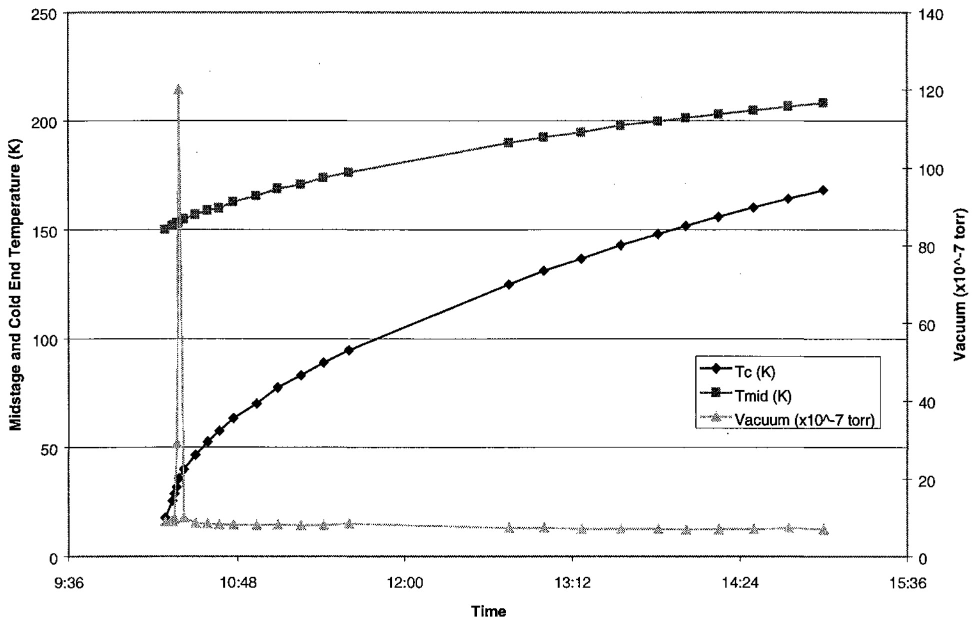

FIGURE 5. Vacuum spike shows release of external contaminants from cold end

contaminants trapped in the multi-layer insulation. Also, as part of the characterization process, the cooler was cycled before each major experiment to minimize contamination on the cold end and to ensure the repeatability of the experimental data.

When the cooler is cycled to drive contamination from the cold end, it is restarted when the cold end warms to approximately 40K. If the cooler is restarted with the cold end between 40K and 55K, a safety trip in the displacer is activated. A stiction test was done on the displacer, but there were no signs of rubbing (Figure 6).

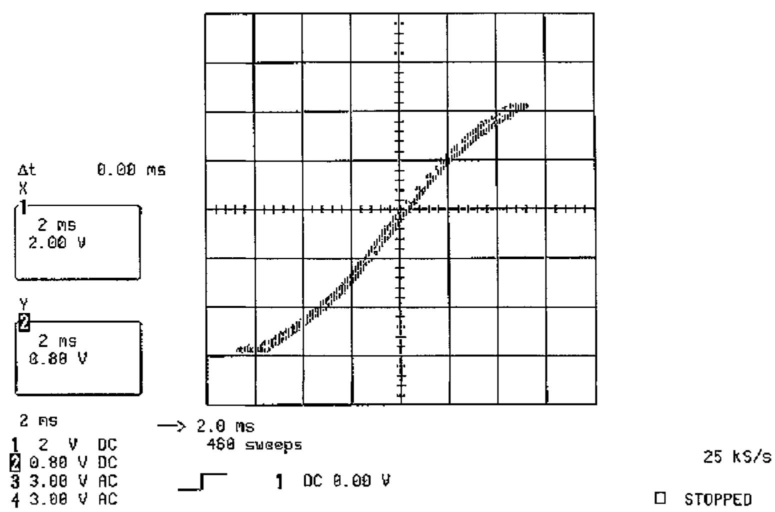

FIGURE 6. Stiction Test Trace for the Displacer

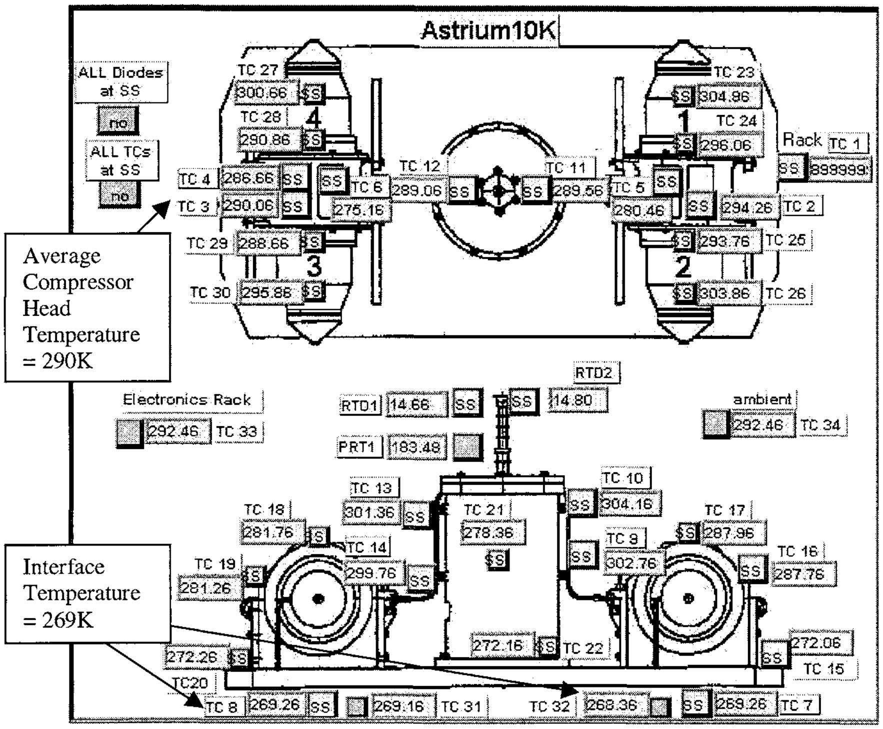

FIGURE 7. Thermal Map of the Astrium 10K Cryocooler

The placement of the thermocouples that monitor heat rejection temperature is also notable. The usual standard is to measure the heat rejection temperature at the interface between the compressors and the heat rejection surface (i.e. the surface between the cooler mount and the spacecraft heat rejection system). By this standard the spacecraft designer can compare the performance of various coolers at a given spacecraft heat rejection temperature. At the Astrium facility, the average of the compressor head temperatures was reported as the heat rejection temperature. The compressor head temperatures were the only readings taken besides the cold end and midstage temperatures. At AFRL, both the temperature of the compressor heads and the temperature at the interface between the mounting plate and the cold plates (which simulates the spacecraft heat rejection interface) are monitored and recorded. The temperature difference between the compressor heads and the cold plate interface is approximately 20K while the cooler is running. For example, if the temperature of the compressor heads is 290K, the temperature of the interface between the mounting plate and the cold plates is approximately 270K. Because the compressor head temperature upper limit is 308K (as set by Astrium), the temperature at the mounting plate interface must be kept below 288K. To allow for data comparison between Astrium data and AFRL data, the heat rejection temperatures reported in this work were defined as the average of the compressor head temperatures. Figure 7 shows a thermal map of the cooler taken during a load line. In this case, the cold end heat load is 250mW with an average heat rejection temperature of 290K. As noted, any realistic integration of this cooler design on a spacecraft bus would require a bus rejection temperature 20K less than the data provided in this report.

FUTURE PLANS

The Astrium 10K cryocooler will go through optimization trials next. These trials investigate the combination of operating parameters that enable optimum cooler performance. In optimization experiments, all controllable operating parameters are kept constant except for one. The one parameter is varied to determine which value provides the most cooling at the lowest temperature and input power. An optimization trial was done at Astrium, so the AFRL optimization trials will be used to verify the optimum values or identify small changes in performance due to experiment stand differences or new operating factors. Phase angle, drive frequency, compressor offset, and expander stroke length will be investigated.

The cooler will also undergo characterization load lines, in which both the heat rejection temperatures and compressor and displacer stroke lengths are varied from their nominal values. These load lines provide engineers with a map of the cryocooler's performance capabilities during steady state operation

Cool down curves at different heat rejection temperatures will also be obtained. These curves allow engineers to predict what the cool down period will be in a real life system. The cooler's cold end temperature stability will also be investigated. The cold end temperature stability trials determine whether or not the cooler can maintain nearly constant low temperature performance without excessive drift rates or excursions that could negatively affect cooled spacecraft components.

The parasitic heat load associated with the cryocooler and its instrumentation will be determined by allowing the cooler to reach steady state at its lowest achievable temperature (with no load), shutting the cooler off, and measuring the cold end warm up rate. At the design point temperature, the warm up rate is proportional to the heat load into the cryocooler's cold end. This procedure is repeated for small loads applied to the cold end. The warm up rate (dT/dt) is plotted against each of the known applied loads. At the no load condition, the temperature rate of change is not zero, due to the fact that the cold end is warming up as a result of the parasitic heat load. By extrapolating the linear proportionality plot for the warm up rates for several artificial heat loads, the parasitic heat load of the cryocooler can be estimated.

Upon completion of the characterization experiments, the Astrium 10K cryocooler will begin an endurance evaluation. The cooler will be run continuously at its normal conditions (45mW @ 10.6K with a heat rejection temperature of 290K) until failure.

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